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PECULIARITIES OF ION FORMATION IN THE F-REGION OF THE IONOSPHERE AND ANOMALIES OF THE COMPOSITE F-LAYER

Code 1

(Osobennosti ionoobrazovaniya v oblasti F ionosfery i anomalii slozhnogo sloya F)

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ABSTRACT

Analysis is made of the altitude and time dependence of the distribution of ion formation intensity in the ionosphere in the case of a complex nonlinear altitude dependence of temperature when only a single gas component is ionized by a quasimonochromatic radiation. It is shown that when the upward movement is accompanied by an abrupt decrease of the temperature gradient, the formation of two maxima of ion production is possible within a certain interval of the Sun's zenith angles. The required conditions for the occurrence of such effect may take place in the F-region of the ionosphere. It appears possible to explain in such a case a number of important features of F_1 and F_2-layers' behavior by the specific features of the fundamental photoionoization process of the atmosphere at the F-region level.

Author

COVER-TO-COVER TRANSLATION

I.

When investigating the processes of formation and development of the ionosphere layer, it is necessary to examine first of all the fundamental processes of atmospheric gases' ionization and of free charge annihilation. At the same time, the establishment of the altitude-time dependence of ion formation intensity $I(z, t)$ is of first rate importance. Function $I(z, t)$ depends first of all on the altitude distribution of the density of the ionized gas $n(z)$. Cases of isothermic atmosphere and of atmosphere with a constant temperature gradient are studied in detail in literature. However, there are a series of indications to the effect, that the temperature is the object of complex variations in the upper atmosphere in space and in time. Particularly complex altitude variations of temperature apparently take place in the F-region of the ionosphere. Computations of temperatures of atmospheric gases on the basis of rocket data, lead, at specific assumptions concerning their composition, to the conclusion, that there is an abrupt break in the curve of altitude dependence of temperature $T(z)$ above 200 km, and that above a certain level the temperature no longer varies with altitude. (see ref. [1, 2]). The curve $T(z)$ for the atmosphere model proposed by Nicolet, and coinciding well with the results of gas density determinations with the aid of satellites [3], shows a sharp break near the 150 km level toward the side where T increase slows down at greater heights. Assumptions are also made about the presence in the ionosphere of local temperature maxima, with which electron density maxima corresponding to ionosphere layers, may be linked in a specific fashion. (see ref. [4]). Models of the F-region of the ionosphere constructed in the assumption of the presence of temperature gradient breaks, have been discussed in literature. Mariani examined, for example, a model of the composite layer of the ionosphere for the case when the temperature has a constant positive gradient below a certain level in the F_1-layer, above which it remains constant [5]. Burkard [6] constructed a model for the F-region for a positive temperature gradient below the F_2-layer maximum, for the temperature constancy near that maximum, and for its negative gradient above it.

The indicated ionosphere models, and more particularly the latter, allow the description of a series of essential traits in the behavior of the F_1 and F_2-layers, and more specifically — of their seasonal variations. The temperature lowering above the F_2-layer maximum, i. e. the presence of the maximum of T at the levels of the F-region of the ionosphere assumed by Burkard, is also entirely plausible. Indeed, the strong decrease with altitude in the rate drop/ of/ of gas density agrees well with the possibility of negative temperature gradients. (see ref. [6, 7]). The assumption about the possibility of a non-monotonous character of the altitude temperature variation is sustained by the general considerations on the heating of the atmospheric gas as a consequence of various physical processes. **At gas' photoionization, part of the ionizing photons' energy is expended on the kinetic energy increase of the then-forming ions,** while as a result of collisions, it is expended on temperature increase **of the total gas, entirely at respective levels [8, 9]. The energy** for gas heating is liberated at recombination processes. Substantial influence is exerted by electromagnetic processes and by magnetohydrodynamic waves on gas heating. The maximum of heating by magnetohydrodynamic waves corresponds to the near 175 km level. In the gas heating taking place in the F-region, electric currents, whose presence was established with the help of satellites, may participate. [11]. All the enumerated processes leading to gas heating are inhomogenous by altitude, and the complex character of the function T (z) in the F-region as well as elsewhere in the ionosphere, may be linked with that fact.

As a consequence there resulted the necessity of conducting the investigation of the function I(z, t) for the case of arbitrary, including also the nonmonotonous dependence T(z), which is precisely carried out in the present work. This allows to expose certain comlementary conditions that may take place in connection with the complex character of T(z) in real conditions.

II

According to contemporary concepts, atomic oxygen is the basic ionizable gas component of the atmosphere in the F-region of the ionosphere. At levels near 200 km, the major part of molecular oxygen apprently is already dissociated. That is why we may admit that in the first approximation the distribution by altitude of atomic oxygen concentration is described above 200 km by the generalized barometric formula

$$n = n_0 \frac{H_0}{H} \exp\left(-\int_{z_0}^{z} \frac{dz}{H}\right). \qquad (1)$$

From the most general considerations concerning the absorption of the ionizing monochromatic emission in the gas layer, the following correlation ensues for the intensity of ion formation I at the level z (neglecting the electron concentration by comparison with that of neutral gas particles) [12] :

$$I = \frac{\sigma S_\infty}{\varepsilon_i} n \exp\left(-\sigma \sec\chi \int_{z}^{\infty} n\, dz\right). \qquad (2)$$

Here σ is the effective cross section of the given process' photoionization, S_∞ is the energy flux of the photoionizing emission at the upper limit of the atmosphere, ε_i is the ionization potential, χ is the Sun's zenith angle. Let us examine the conditions of formation of function's I (z) extremes. The extremeness condition of I (z) may be obtained from the expression (2) in the form

$$\cos\chi = \sigma f(z), \qquad (3)$$

where

$$f(z) = -\frac{n^2}{\frac{dn}{dz}}. \qquad (4)$$

At the condition that the concentration of the ionizable gas is distributed in altitude according to the law (1), function f (z) may be written in one of the following two expressions :

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$$f(z)=\frac{nH}{1+\frac{\partial H}{\partial z}}=n_0H_0\frac{\exp\left(-\int\limits_{z_0}^{z}\frac{dz}{H}\right)}{1+\frac{\partial H}{\partial z}}\qquad(5)$$

or

$$f(z)=n_0T_0\frac{\exp\left(-C\int\limits_{z_0}^{z}\frac{dz}{T}\right)}{C+\frac{\partial T}{\partial z}},\qquad(6)$$

where $C = mg/k$. These expressions are valid for one gas or for gas mixture in case of their full intermixing, when the mean molecular weight does not vary with altitude. The constancy of g is assumed in the examined altitude range. In cases of isothermic atmosphere or constant temperature gradient, when the denominator in the expressions (5) and (6) is equal to the unity or to another constant magnitude, **function $f(z)$ is exponential, monotonously decreasing with the altitude. This corresponds to one maximum of $I(z)$, dropping downward at the in-**crease of $\cos\chi$, as it follows from the expression (3). If the derivatives $\partial H/\partial z$ or $\partial T/\partial z$ **are decreasing functions of altitude, there** appears a possibility of nonmonotonous variation of $f(z)$. The function $f(z)$ may have maxima and minima under specific conditions. The analysis at the extreme of the expression (5) or (6) gives the following extremeness conditions for the function $f(z)$:

$$-\frac{\partial^2 H}{\partial z^2}=\frac{1+\frac{\partial H}{\partial z}}{H},\quad\frac{\partial^2 H}{\partial z^2}<0\qquad(7)$$

or

$$-\frac{\partial^2 T}{\partial z^2}=C\frac{C+\frac{\partial T}{\partial z}}{T},\quad\frac{\partial^2 T}{\partial z^2}<0.\qquad(8)$$

If in the altitude range adjacent to level of the $f(z)$ extreme either of the two following inequalities takes place :

$$-\frac{\partial^2 H}{\partial z^2}>\frac{1+\frac{\partial H}{\partial z}}{H}\qquad(9)$$

or

$$-\frac{\partial^2 T}{\partial z^2}>C\frac{C+\frac{\partial T}{\partial z}}{T},\qquad(10)$$

the examined extremum is the maximum or the minimum of $f(z)$.

In such case the condition of I (z) extremeness expressed in (3), may be simultaneously satisfied at two different levels situated above and below the maximum and minimum level of the function f (z). It follows from the general considerations relative to the character of the function f (z), that it may have no less than two extremes corresponding to $\partial^2 f/\partial z^2 \neq 0$ (i. e. maximum or minimum). It is indeed visible from the expressions (5) and (6) that function f (z) has a decreasing character (with altitude). Thus if I_{max} exists, I_{min} must also necessarily exist, for f (z) cannot increase unboundedly as z increases. Besides, magnitude f(z) may remain constant within a certain altitude range, provided equalities (7) and (8) are satisfied within it. Therefore, if inequalities (9) or (10) are satisfied **in a certain altitude interval, I (z) has three extremes for specific values of cos χ, two of which are maxima, and one — minimum,** in between. In reality, a direct analysis in the extreme of expression (2) shows, that when condition (1) is respected, correlation (6) corresponds to the minimum of I (z), and correlations (7) and (8) — — to the inflexion of I (z) when $\partial I/\partial z = 0$. Therefore, in that altitude interval, inequalities (9) or (10) are satisfied, only a minimum of I (z) may form, i. e. there is in that case a forbidden altitude range for the formation of a maximum of I (z). For the corresponding magnitude cos χ the curve I (z) is distorted in such a way, that two maxima are forming, one of which is situated above the altitude range out of bounds for I_{max}, the other — below it. A peculiar break up of maximum I takes place. At the boundaries of the altitude range, forbidden for the I_{max}, where the equalities (7) and (8) are fulfilled, only the inflexion I (z) may form. In the simplest case of the examined situation, function f (z) may be represented as shown in Fig. 1.

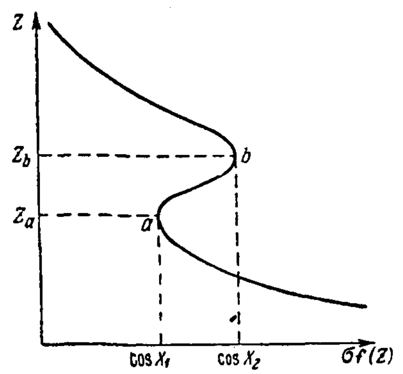

Fig. 1. Possible character of the dependence on cos χ of the altitude of extreme magnitudes of ion formation intensity.

As $\cos\chi$ grows, the maximum of ion formation slides along the upper branch of the curve $\sigma f(z)$ — downward. At the moment when $\cos\chi = \cos\chi_1$, an inflexion of $I(z)$ forms at the z_a level, then I_{min} forms in the interval (z_a, z_b) at $\cos\chi > \cos\chi_1$, while I_{max} forms below the level I_a. Two maxima I exist at $\cos\chi_1 < \cos\chi < \cos\chi_2$ one of which is disposed above the level z_b, the other — below z_a. At $\cos\chi = \cos\chi_2$ the upper maximum I transforms into an inflexion and one lower maximum I remains at $\cos\chi > \cos\chi_2$. The fact that in the $\chi_1 - \chi_2$ interval of the values of Sun's zenith angle the lower maximum I develops from the inflexion* attests that the relation between the magnitudes of the upper and lower maxima then decreases.

The examined situation may be created at a slowed down temperature growth or ionizable gas'scale increase, and also — at an accelerated decrease of these parameters with altitude. The greater the magnitude of that acceleration, the faster this situation is to develop. i.e. $|\partial^2 H / \partial z^2|$. To satisfy the inequalities (9) and (10), the greater is the magnitude T (or H), the smaller will be the required acceleration's magnitude. In this regard, the most favorable conditions exist for the atomic oxygen in the F-region. The atmosphere height H brought forth for it, has for the given temperature the greatest magnitude in comparison with other gases (except the atomic nitrogen). In the F-region of the ionosphere highest gas temperatures are reached in conjunction with the possibility of sharp variations of their gradients. All this creates favorable conditions in the F-region for the existence of an altitude range, forbidden for I_{max} in the case of a sharp decrease of temperature rise with altitude, or of the presence of the maximum $T(z)$. In the latter case the inequalities (9) and (10) may be satisfied below the T_{max} level, at that level, and above it. These inequalities are most easily satisfied above T_{max}, provided an accelerated temperature decrease with altitude takes place there.

*[insert here the following] :
"and the other transforms into the inflexion for $\cos\chi$ increase"

To fulfill the inequalities (9) and (10) at $H = 60$ km for the atomic oxygen and a positive temperature gradient of 4 deg/km (to which corresponds $\partial H/\partial z = 0.23$ at $g = 908$ cm/sec^2 at the 250 km level), module $\partial^2 H/\partial z^2$ must be greater than 0.020 km^{-1}, and module $\partial^2 T/\partial z^2$ must be greater than 0.36 deg/cm^2. For $\partial T/\partial z = 0$ at the T_{max} level, module $|\partial^2 H/\partial z^2|$ must be greater than 0.017 km^{-1}, but for $\partial T/\partial z = -4$ deg/km $\partial^2 H/\partial z^2$ must be greater than 0.013 km^{-1}.

It may be seen from the expression (4) that function $f(z)$ may be nonmonotonous within a certain altitude range in the case when there takes place a sufficiently great slowing down in gas density drop with altitude.

The available data on atmosphere structure at ionospheric levels do not provide as yet the possibility of visualizing the true distribution with altitude of atomic oxygen density. However, curves of altitude dependence of the relation $\rho^2/(\partial\rho/\partial z)$, plotted according to data on gas density distribution obtained with the help of rockets and satellites [13 – 15], reveal signs of nonmonotonous variation within the 160 – 270 km limits. The data brought out in the indicated sources have a time and space-averaged character, except for reference [15], where results of gas density measurements obtained in the course of a single rocket flight are brought forth. In the latter case, the nonmonotony of $f(z)$ has the clearest character. This is possibly linked with the fact that the distribution of $\rho(z)$ changes markedly in time as well as in space, and that the averaging levels down the effect we search for. From the standpoint of the examined effect, the atmosphere model constructed according to rocket data –"the C-model of 1958" – offers interest. The striking feature of that model is the convexity in the curve $\rho(z)$, clearly expressed at levels of the F-region of the ionosphere. This point to the possibility of not quite monotonous a distribution of gas density in that part of the atmosphere, which should reinforce the effect sought for. At 180 –210 km levels the curve $f(z) = -\rho^2/(\partial\rho/\partial z)$

for that model has a nonmonotonous character.

The examined nonmonotony of $f(z)$ cannot however be unilaterally interpreted as a consequence of sharp variation of temperature gradient or of temperature maximum presence, for such effect in $f(z)$ may also induce a probable retardation in the rate of drop with altitude of gas' mean molecular weight. This is visible from the equality

$$\frac{dH}{H} = \frac{dT}{T} - \frac{dm}{m} - \frac{dg}{g}, \qquad (11)$$

that follows from the determination of H [17].

If the distribution by altitude of the density of the ionizable gas $\rho(z)$ is known, one may obtain the magnitude I of ion formation intensity at various heights in relation to the magnitude I^* at a certain arbitrarily chosen level z^*, as this follows from the expression (2) :

$$I/I^* = n/n^* \exp\left(-\sigma \sec\chi \int_z^{z^*} n dz\right). \qquad (12)$$

The computations for hypothetical distributions of $n(z)$ corresponding to the clearly-defined region forbidden for I_{max}, show that the time variations of $I(z)$ must in that case have the character indicated in Fig. 2. As the growing $\cos\chi$ nears the value of $\cos\chi_1$, an inflexion begins to develop at the z_a level in the curve of altitude distribution of $I(z)$, and $\partial I/\partial z$ becomes zero at the z_a level when $\cos\chi = \cos\chi_1$. Prior to that moment, there exists a single upper maximum I, dropping and rising in magnitude with the growth of $\cos\chi$. At $\cos\chi > \cos\chi_2$, a lower maximum I forms below the z_a level, that rises quickly at the further increase of $\cos\chi$. As a result, the correlation between the magnitudes of the upper and lower maxima I, diminishes fast. At the same time the minimum I ascends upwards. The upper maximum I levels down quickly as $\cos\chi$

nears the cos χ_2 value, and transforms into an inflexion at the z_b level at cos χ = cos χ_2. At cos χ > cos χ_2 a single lower maximum I continues to develop, and the basic dose of the forming ionization corresponds then to levels lying below z_a. Traces of the upper maximum I remain at the z_b level when cos χ > cos χ_2, but they smooth down as the difference (cos χ — cos χ_2) increases.

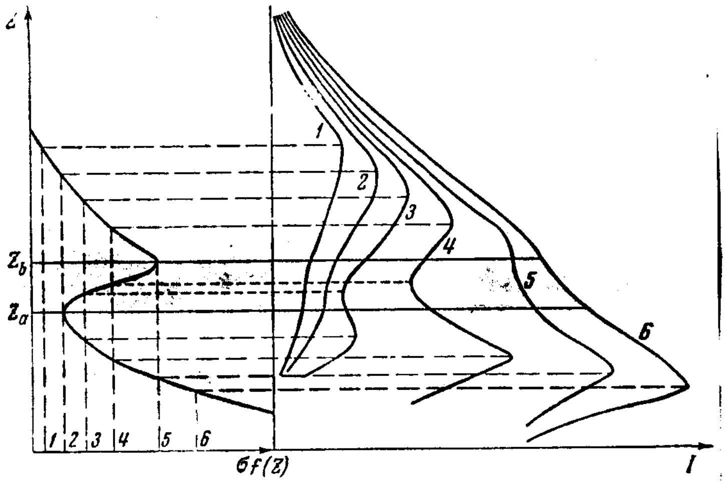

Fig. 2. Block diagram of the altitude distribution of ion formation intensity I (z) for various values of cos / (at the right) in the case, when function f (z), plotted at the left, has a maximum.

From the viewpoint of the integral magnitude of ion (and electron) formation, one may state, that the presence of a region forbidden for I_{max}, accelerates and strengthens the process of ion formation intensity redistribution by altitude, and in such a fashion, that the fundamental dose of ionization falls on the lower levels.

III

The described splitting process of ion formation maximum, possible at the F-region of the ionosphere levels, permits the interpretation of certain essential peculiarities of the behavior of F1 and F2 -layers in the middle latitudes, heretofore not having been the object of a full, universally-accepted explanation.

As is well known, the winter behavior of the F_2-layer, and also in the course of a substantial part of the equinoctial season, reminds of the plain layer (near-midday maximum f_oF2, daylight minimum h_pF2). The F_1- layer seldom appears in winter at latitudes above 45^o, and when it does so, it takes place nearly every time at about midday. It occurs earlier and more often with the seasonal rise of cos χ. But in summer it is nearly always observed in daytime. The transit from the winter to the summer type of the F_2-layer is linked with the development of the F_1- layer. The behavior of the latter year-round is close to that of the plain layer in the sense of the dependence on cos χ of its critical frequencies.

Thus, two layers exist in the F-region of the ionosphere during the equinoctial period, whose behavior pattern responds in the the first approximation to that of the plain layer.

It is well known that one of the basic conditions of existence of the plain layer is the formation of electron density maximum at the level of the maximum of ion formation intensity, or near it. It would thus be natural to assume, that two maxima I exist in the F-region of the ionosphere during part of the equinoctial season, one of which corresponds to the F_1- layer, and the other — to the F_2 - layer. At the same time, one of them forms only in near-midday hours, and is not always clearly defined. The transition from the winter type of the F_2-layer, when it forms near the upper maximum I, to the summer type, when its formation may be well explained on the basis of the Bradbury scheme [18], may be connected with the gradual disappearance of the upper maximum I, and the development of the lower one. The described peculiarities of the seasonal variation of the F_1 and F_2 - layers, and the designated scheme of corresponding seasonal variations of maxima of ion formation intensity may be explained in the following fashion.

If cos $\chi <$ cos χ_1 in winter time (see Fig. 1), there should be one maximum I above the z_b level. The F_2-layer may correspond to that maximum. At near summertime, the midday cos χ begins to exceed the magnitude cos χ_1 insignificantly at the beginning, then gradually more and more. To this corresponds the appearance of the inflexion, and then also of a weakly-defined maximum below the z_a level. Conditions for the formation of a maximum in the altitude distribution of the electron concentration are created in the same manner. It corresponds to the F-layer, weakly expressed at first, and more sharply later on. Simultaneously with the existence of two maxima I near noon time at $\cos \chi_1 < \cos \chi < \cos \chi_2$ one may link the presence of the two layers — F_1 and F_2, similar in some respect to the plain layer. Such is the way the situation in the F-region of the ionosphere may represented in the equinoctial season.

The transition to summer conditions may be connected with the reaching by the cosine of Sun's zenith angle of the value $\cos \chi_2$. At the same time, the upper maximum I, with which, according to our assumption, the winter F_2- layer is linked, passes into the inflexion, and then disappears completely, while the lower maximum increases. At the latter's level the summer F_1-layer continues to develop. As to the F_2-layer, it is formed an account of the effect of charge accumulation at levels with long average lifetime of the free charges according to the Bradbury scheme.

On the basis of the aforesaid, the pattern of the anomalous seasonal course of F_2-layer's critical frequencies at midday. The rise of f_0F_2 from January to April is related to the seasonal increase of the upper maximum I. the ensuing decrease of midday f_0F_2 is linked with the levelling down of that maximum and the transition to summer conditions. The seasonal variation of the F-region of the ionosphere may similarly be represented for the second half of the year, when the midday height of the Sun decreases.

There exists the assumption, that the irregular orbital accelerations of satellites [19], are connected with temperature and gas density increase [20]. Variations of gradients $\partial\rho/\partial z$ must then take place, which in in its turn must lead to the appearance or strenghtening of the effect described in the present paper.

Perhaps the episodic appearance of the F_1-layer during winter months at middle latitudes precisely is the consequence of such increase in temperature and gas density at levels of the F-region of the ionosphere ?

In connection with this, the problem may be set up of the emergence of a possible correlation between satellite deceleration and the appearance during winter months of the F_1-layer at middle latitudes.

In conclusion, I wish to express my thanks to the acting chief of the radiophysics chair at the Irkutsk State University in the name of A. A. Zhdanov — lecturer V. M. Polyakov, for his every-day attention in the conducting of the present work, for his counsel and indications.

******** THE END ********

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